PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :		(11) International Publication Number:	WO 98/09241
G06F 19/00, A61B 5/042	A1	(43) International Publication Date:	5 March 1998 (05.03.98)

(21) International Application Number: PCT/CA97/00615

(22) International Filing Date: 27 August 1997 (27.08.97)

(30) Priority Data:

08/705,621	29 August 1996 (29.08.96)	US
08/846,348	30 April 1997 (30.04.97)	US

(71) Applicant: HARLEY STREET SOFTWARE LTD. [CA/CA]; 771 Vanalman Avenue, Victoria, British Columbia V8Z 3B8 (CA).

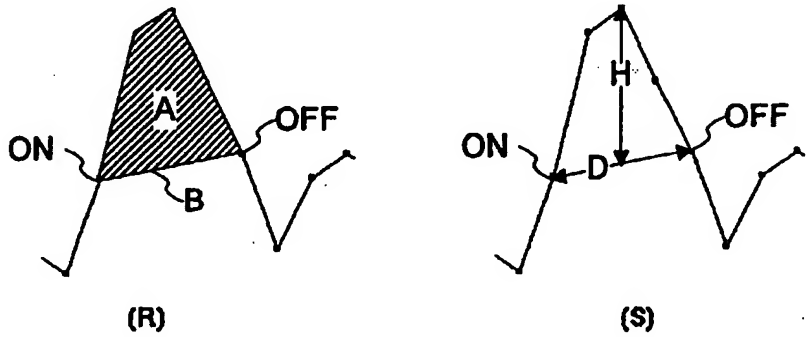
(72) Inventors: BURTON-KRAHN, Noel, Morgen; 4050 Quadra Street, Victoria, British Columbia V8X 1K3 (CA). ILLNER, Reinhard; 1621 Prairie Street, Victoria, British Columbia V8N 5X9 (CA). STEACY, Robert, Clifford, Bruce; 641 Rodolph Road, Victoria, British Columbia V8Z 5W3 (CA).

(74) Agent: WIGGS, Blake, R.; Oyen Wiggs Green & Mutala, 480 - 601 West Cordova Street, Vancouver, British Columbia V6B 1G1 (CA).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, UZ, VN, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: ECG P-QRS-T ONSET, OFFSET AND PEAK DETECTION METHOD AND APPARATUS



(R) (S)

(57) Abstract

A method and apparatus for detecting P or T waves in an electrocardiogram signal in intervals before and after each (previously) detected QRS wave. Within each interval, a candidate pair of samples are selected. If the candidate pair are separated by a time duration which does not exceed a predefined time duration then that pair is rejected and the process repeats. Otherwise, the area "A" of a closed polygon bounded by all of the samples between and including the candidate pair is derived (the polygon's base line extends linearly a distance "d" between the candidate pair of sample intervals). The maximum vertical displacement "h" between the base line and any portion of the polygon above the base line is derived. If "h" does not exceed a predefined minimum vertical displacement, then the candidate pair is rejected and the process repeats. Otherwise, a value Gamma = A*h/d is derived for the candidate pair. If Gamma does not exceed any value of Gamma derived previously in respect of any previously selected candidate pair, then the candidate pair is rejected and the process repeats. Otherwise, a value BestGamma is set equal to the candidate pair's value Gamma. Another candidate pair is then selected and the process repeats. The P or T wave is selected as that whose value Gamma equals the value BestGamma.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

ECG P-QRS-T ONSET, OFFSET AND PEAK DETECTION METHOD AND APPARATUS

Field of the Invention

This application pertains to identification of P, T and QRS waves in electrocardiogram ("ECG") signals.

Background of the Invention

ECG signals are obtained by applying adhesive patch or metal plate electrodes to a patient's chest and connecting the electrodes to a cardiograph machine. The cardiograph measures voltage differences between pairs of electrodes. The voltage difference between each pair of electrodes is a "lead". The cardiograph sequentially measures the leads at regular time intervals and stores the measurements. A sequence of such measurements is referred to as set of "ECG samples". The "sampling rate" is the frequency at which the measurements are made. Sampling rates of 125, 250, 500, or 1000 samples per second are typical. Typical ranges for the measurements are -5mV to +5mV, divided into 2^8, 2^{12}, or 2^{16} measurement intervals.

Figure 1 depicts a typical ECG signal consisting of several heart beat segments. Each beat of a patient's heart produces a unique ECG signal segment, such as the single heart beat cycle ECG signal segment shown in Figure 2. According to well known principles of cardiology, each heart beat cycle typically includes a "P" wave 10, a "QRS" wave 12 and a "T" wave 14. Each of these waves is representative of a particular characteristic of the patient's heart beat.

Each P, QRS, and T wave begins at a specific "onset" and ends at a specific "offset". Each wave also has a "peak", which is the wave's maximum displacement relative to a predefined "baseline". However, electrodes placed in different locations on the same patient yield different ECG signals in response to the same heart beat. Accordingly, variations from lead to lead in the onset, offset, and peak values for each P, QRS, and T wave are common. For some

leads in some ECG signals, a P, QRS or T wave may not be evident at all.

The aforementioned "baseline" is the electrical signal measured by the cardiograph in the absence of cardiac activity. The baseline is not flat, but wanders up and down as the patient's body moves. Accordingly, P, QRS and T waves are not seen relative to a flat horizontal line, but relative to a wandering baseline, as shown in Figure 3. Variations in ECG signal measurements can also result from noise introduced by movement of the patient's body, electromagnetic interference, etc. For example, patient muscle activity can introduce high frequency noise as shown in Figure 4. Such noise can be of the same amplitude as the P or T waves, and must be removed for accurate measurement of P or T waves.

Various prior art techniques have been devised to detect P, QRS, or T waves in ECG signals. For example, Pan et al use a moving window integrator to detect QRS waves, but make no attempt to detect P or T waves (see Pan, J. and Thompkins, W. J.; "A Real-Time QRS detection Algorithm", IEEE Transactions on Biomedical Engineering, vol. 32, pp. 230-236, 1985).

Reddy, et al use a derivative and threshold technique to detect P waves (see Reddy, et. al; "Detection of P Waves in Resting ECG: A Preliminary Study"; IEEE, 1992). However, because derivatives are affected both by baseline wander and by noise, this technique is susceptible to error in the presence of either baseline wander or noise, both of which are common.

Laguna, et al use the signal slope to identify the QRS wave, use derivatives to find the peaks of the P and T waves, and use derivatives and thresholding to find the onsets and offsets of the P and T waves (see Laguna, et al.; "Automatic Detection of Wave Boundaries on Multilead ECG Signals: Validation with the CSE Database"; Computers and Biomedical Research, vol. 27, pp. 45-60, 1994). This

method is also error-prone in the presence of baseline wander or noise.

Koski, et al use syntactic methods based on signal slope to identify P, QRS, and T waves (see Koski, et al; "Syntactic Recognition of ECG Signals by Attributed Finite Automata"; 1995). This method is also believed to be error-prone in the presence of baseline wander or noise.

United States Patent No. 4,945,917 Akselrod, et al discloses a technique for detecting fetal QRS waves in which maternal QRS waves are first detected in an operator-assisted "learning" phase by deriving first and second derivatives of a portion of the maternal ECG signal. A "template" representative of the maternal QRS wave is then constructed and subtracted from a composite maternal-fetal ECG signal to derive the fetal QRS wave. This technique is subject to a number of disadvantages, including the need for operator intervention, and reliance upon a fixed template which may be a poor representation of the continuously variable QRS wave as the patient's heart beat conditions vary.

United States Patent No. 4,704,681 Shimuzu, et al discloses an apparatus for detecting certain "delta waves" within previously detected QRS waves. No provision is made for detecting P or T waves.

The present invention provides a method and apparatus for reliably, automatically detecting P, QRS and T waves in high speed processing of large volumes of ECG signal data representative of multiple leads and many heart beat cycles.

Summary of the Invention

The invention provides a method and apparatus for detecting P or T waves in an electrocardiogram signal in intervals before and after each (previously) detected QRS wave. Within each interval, a candidate pair of samples are selected. If the candidate pair are separated by a time duration which does not exceed a predefined time

duration then that pair is rejected and the process repeats. Otherwise, the area "A" of a closed polygon bounded by all of the samples between and including the candidate pair is derived (the polygon's base line extends linearly a distance "d" between the candidate pair of samples). The maximum vertical displacement "h" between the base line and any portion of the polygon above the base line is derived. If "h" does not exceed a predefined minimum vertical displacement, then the candidate pair is rejected and the process repeats. Otherwise, a value Gamma = A*h/d is derived for the candidate pair. If Gamma does not exceed any value of Gamma derived previously in respect of any previously selected candidate pair, then the candidate pair is rejected and the process repeats. Otherwise, a value BestGamma is set equal to the candidate pair's value Gamma. Another candidate pair is then selected and the process repeats. The P or T wave is selected as that whose value Gamma equals the value BestGamma.

Brief Description of the Drawings

Figure 1 depicts a typical ECG signal consisting of several heart beat cycle segments.

Figure 2 depicts a single heart beat cycle segment of the Figure 1 ECG signal.

Figure 3 depicts a single heart beat cycle segment of the Figure 1 ECG signal in which the ECG baseline is wandering.

Figure 4 depicts a single heart beat cycle segment of the Figure 1 ECG signal in which the signal is contaminated by high frequency noise.

Figure 5 is a block diagram of a P, QRS, and T wave detector according to the invention.

Figures 6A and 6B together comprise a flowchart which depicts the sequence of steps performed in detecting QRS waves in accordance with the invention.

Figure 7 is a flowchart which depicts the sequence of steps performed in detecting P or T waves in accordance with the invention.

Figure 8 is a flowchart which depicts the sequence of wave detection sub-steps performed during either P or T wave detection in accordance with the invention.

Figures 9A through 9S are signal waveforms which respectively depict successive stages of the operation of the preferred embodiment of the invention.

Detailed Description of the Preferred Embodiment

Introduction

Figure 5 is a block diagram representation of an apparatus for processing previously measured and stored ECG samples 20 in accordance with the invention. Each ECG sample waveform is generally of the form shown in Figure 9A, which is identical to the previously discussed Figure 2 waveform. Buffer 21 stores a selected group of ECG samples while approximations to the first and second derivatives of those samples are derived.

Specifically, filter 23 receives the Figure 9A ECG sample waveform as input, and produces as output a signal representative of the first derivative ("D1") thereof, as shown in Figure 9B. Filter 26 also receives the Figure 9A ECG sample waveform as input, and produces as output a signal representative of the second derivative ("D2") thereof, as shown in Figure 9C. Buffer 24 stores the first derivative representations output by filter 23, and buffer 27 stores the second derivative representations output by filter 26.

As hereinafter described in greater detail, QRS detector 22 applies the algorithm depicted in Figures 6A and 6B to the ECG samples stored in buffer 21, to the first derivative representations stored in buffer 24 and to the second derivative representations stored in buffer 27 to detect the onsets, peaks, and offsets of QRS waves in each

ECG sample waveform. P and T wave detector 25 applies the algorithm depicted in Figur 7 to the output of QRS detector 22 and to the ECG samples stored in buffer 21 to detect the onsets, peaks, and offsets of the P and T waves in each ECG sample waveform. The onsets, offsets, and peaks of the P, QRS, and T waves output by QRS detector 22 and by P and T detector 25 are stored as a sequential record 28, which can be on a computer disk, tape, memory, or communications channel.

QRS Wave Detection

The operation of QRS detector 22 will now be described with reference to Figures 6A and 6B. Such operation is conveniently characterized in terms of the following definitions:

MaxQRSSep	absolute maximum distance between QRS waves
MaxSep	maximum distance between QRS waves
MinQRSSep	absolute minimum distance between QRS waves
MinSep	minimum distance between QRS waves
MinQRSWidth	absolute minimum time between QRS wave onset and offset
MaxQRSWidth	absolute maximum time between QRS wave onset and offset
MinQRSHeight	absolute minimum height from onset or offset to peak
MaxWidth	maximum time between QRS wave onset and offset
MinWidth	minimum time between QRS wave onset and offset
MinHeight	minimum height from onset or offset to peak
D2Thresh	minimum value of second derivative at QRS peak
MinD2Height	minimum height from onset or offset to peak in second derivative
QRSPeak	peak of current candidate QRS wave
QRSOn	onset of current candidate QRS wave
QRSOff	offset of current candidate QRS wave
LastQRSPeak	peak of previously detected QRS wave
LastQRSOn	onset of previously detected QRS wave
LastQRSOff	offset of previously detected QRS wave

An initialization step 40 is first performed to set the following initial values:

MaxQRSSep	:=	2 seconds
MaxSep	:=	MaxQRSSep
MinQRSSep	:=	0.2 seconds
MinSep	:=	MinQRSSep
MinQRSWidth	:=	25 milliseconds
MaxQRSWidth	:=	240 milliseconds
MinQRSHeight	:=	0.25mV
MaxWidth	:=	MaxQRSWidth
MinWidth	:=	MinQRSWidth
MinHeight	:=	MinQRSHeight
D2Thresh	:=	0
MinD2Height	:=	0
D1Lthresh	:=	0
D1Rthresh	:=	0
D2LRThresh	:=	0
LastQRSPeak	:=	nil
LastQRSOn	:=	nil
LastQRSOff	:=	nil

At step 41, the next ECG sample is retrieved from buffer 21, and that sample (called "QRSPeak") is evaluated to determine whether a QRS wave can be detected therein. Step 41 is the first step in a loop. QRSPeak is incremented by one with each repetition of step 41. At step 44, a test is performed to determine whether the distance 90 (Figure 9D) between the peak of the current candidate QRS wave (i.e. QRSPeak) and the peak of the previously detected QRS wave (i.e. LastQRSPeak) is less than the maximum distance between QRS waves (i.e. MaxSep), or whether LastQRSPeak is nil (as it will be if the current candidate QRS wave is the first sample processed from buffer 21).

If distance 90 is not less than MaxSep, or if LastQRSPeak is nil, then a further test step 45 is performed to determine whether threshold values D2Thresh, MinD2Height, MinHeight and MinWidth are minimal. These threshold values are minimal if the following conditions are met:

D2Thresh	≤	0
MinD2Height	≤	0
MinHeight	≤	MinQRSHeight
MinWidth	≤	MinQRSWidth

If the threshold values D2Thresh, MinD2Height, MinHeight and MinWidth are not minimal, then step 43 is performed to relax those threshold values, as well as the threshold

values MaxSep, MinSep, MaxWidth by resetting their respective values as follows:

```
MaxSep      :=  Min(MaxQRSSep, MaxSep*2)
MinSep      :=  Max(MinQRSSep, MinSep/2)
MaxWidth    :=  MIN(MaxQRSWidth, MaxWidth*2)
MinWidth    :=  MAX(MinQRSWidth, MinWidth/2)
MinHeight   :=  MAX(MinQRSHeight, MinHeight/2)
D2Thresh    :=  2
MinD2Height :=  2
```

After relaxation step 43, step 42 is performed to reset the previously detected QRS wave (i.e. LastQRSPeak) as the sample to be evaluated, commencing with step 41, to determine whether a QRS wave can be detected therein. Accordingly, the candidate QRS wave which was unsuccessfully processed during the previously described steps will again be processed, with different threshold values, to determine whether a QRS wave can be detected therein. If test step 45 determines that threshold values D2Thresh, MinD2Height, MinHeight and MinWidth are minimal, then step 46 is performed to output the last QRS and to set LastQRSPeak to nil.

At this point, QRS detector 22 has reached a stage at which the QRS wave following an earlier-detected QRS wave can not be detected. A detected QRS wave is not immediately output, because it may be invalidated by a subsequently detected QRS wave. If no following QRS wave is detected, then the last detected QRS wave is accepted as valid and its onset, offset and peak values are output. Once a QRS wave is output, it need not be retained in memory. Since no new QRS wave has been detected, LastQRSPeak is set to nil.

After performance of step 46; or, if test step 44 determines that distance 90 is less than MaxSep, and that LastQRSPeak is not nil, then a further test step 47 is performed on the second derivative representation (input to QRS detector 22 from buffer 27) of the ECG sample currently being processed by QRS detector 22. As depicted in Figure 9E, test step 47 determines whether the second derivative at QRSPeak is a local extrema. If the ECG sample currently

being processed by QRS detector 22 is sample "i", then its second derivative is a local extrema if and only if D2[i-1] ≤ D2[i] ≥ D2[i+1]; or, D2[i-1] ≥ D2[i] ≤ D2[i+1].

If test step 47 determines that the second derivative at QRSPeak is not a local extrema, then the loop is repeated commencing with step 41. Otherwise, if test step 47 determines that the second derivative at QRSPeak is a local extrema, then a further test step 48 is performed to determine whether the absolute value of the second derivative at QRSPeak is less than D2Thresh, as shown in Figure 9F. If test step 48 determines that the absolute value of the second derivative at QRSPeak is less than D2Thresh, then the loop is repeated commencing with step 41. Otherwise, if test step 48 determines that the absolute value of the second derivative at QRSPeak is less than D2Thresh, step 49 is performed to set indices D2On, D2Off (Figure 9F) equal to the indices of the local extrema adjacent QRSPeak in the second derivative of the ECG sample currently being processed by QRS detector 22.

After performance of step 49, a further test step 50 is performed to determine whether the time "t1" (Figure 9G) between D2Off and D2On is less than MaxWidth. If test step 50 determines that the time between D2Off and D2On is not less than MaxWidth, then the loop is repeated commencing with step 41. Otherwise, if test step 50 determines that the time between D2Off and D2On is less than MaxWidth, then a further test step 51 is performed to determine whether the minimum difference in the values "a", "b" (Figure 9G) of the second derivative between D2On and D2Peak or between D2Off and D2Peak are less the MinD2Height.

If test step 51 determines that the minimum difference in the values of the second derivative between D2On and D2Peak; or, between D2Off and D2Peak are not less the MinD2Height, then the loop is repeated commencing with step 41. Otherwise, if test step 51 determines that the minimum difference in the values of the second derivative between D2On and D2Peak; or, between D2Off and D2Peak are less the

MinD2Height then step 52 is performed to set threshold values D1LThresh, D1RTthresh for the first derivative, and to set threshold value D2LRThresh for the second derivative between D2On and D2Off, as shown in Figure 9H. More particularly, the threshold values are set as follows:

D1LThresh := ¼ the maximum value in the first derivative between D2On and QRSPeak

D1RThresh := ¼ the maximum value in the first derivative between QRSPeak and D2Off

D2LRThresh := ¼ the maximum value in the second derivative between D2On and D2Off

After performance of step 52, step 53 is performed, as depicted in Figure 9I, to set QRSOn and QRSOff to the indices near QRSPeak where the values of the first and second derivatives are below D1Lthresh and D2LRThresh for QRSOn, and below D1RThresh and D2LRThresh for QRSOff.

After performance of step 53, test step 54 is performed to determine whether the time "t2" (Figure 9J) between QRSOn and QRSOff is less than MaxWidth. If test step 54 determines that the time between QRSOn and QRSOff is not less than MaxWidth, then step 55 is performed to set QRSOn and QRSOff equal to D2On and D2Off respectively (Figure 9K). If test step 54 determines that the time between QRSOn and QRSOff is less than MaxWidth; or, after performance of step 55 if needed, test step 56 is performed to determine whether the average height difference from QRSOn to QRSPeak (i.e. distance "a" in Figure 9L); and, from QRSOff to QRSPeak (i.e. distance "b" in Figure 9L) is less than MinHeight. If test step 56 determines that the average height difference aforesaid is not less than MinHeight, then the loop is repeated commencing with step 41.

Otherwise, if test step 56 determines that the average height difference aforesaid is less than MinHeight then a test step 57 is performed to determine whether LastQRSPeak is nil (i.e. to determine whether LastQRSPeak has been accepted as a QRS wave). If test step 57 determines that LastQRSPeak is not nil, then a further test step 58 is performed to determine whether the time "t3" (Figure 9M)

between LastQRSPeak and QRSPeak is greater than MinSep. If test step 58 determines that the time between LastQRSPeak and QRSPeak is greater than MinSep, then LastQRSPeak is accepted as a valid QRS wave and is as such at step 59. Otherwise, if test step 58 determines that the time between LastQRSPeak and QRSPeak is not greater than MinSep, then a further test step 60 is performed as depicted in Figure 9N to determine whether the absolute value "V1" of the second derivative at QRSPeak is greater than its absolute value "V2" at LastQRSPeak. If test step 60 determines that V1 is not greater than V2, then the loop is repeated commencing with step 41. Otherwise, if test step 60 determines that V1 is greater than V2; or, if test step 57 determines that LastQRSPeak is nil; or, after performance of step 59; step 61 is performed to derive a QRS model from the current QRS candidate as follows:

MaxSep	:=	2*(QRSPeak - LastQRSPeak), or MaxQRSSep if LastQRSPeak is nil
MinSep	:=	½*(QRSPeak - LastQRSPeak), or MinQRSSep if LastQRSPeak is nil
MaxWidth	:=	Min(2*(QRSOff - QRSOn), QRSMax-Width)
MinWidth	:=	Max(½*(QRSOff - QRSOn), QRSMin-Width)
MinHeight	:=	Max(½*(height of QRS), QRSMin-Height)
D2Thresh	:=	½*(Abs(D2) at QRSPeak)
MinD2Height	:=	½*(height of QRS in D2)

After performance of QRS model derivation step 61, step 62 is performed to set LastQRSPeak, LastQRSOn, and LastQRSOff equal to the values of QRSPeak, QRSOn, and QRSOff respectively. After performance of step 62, the loop is repeated commencing with step 41.

P and T Wave Detection

The operation of P and T detector 25 will now be described with reference to Figure 7. As previously mentioned, P and T wave detector 25 applies the Figure 7 algorithm to the output of QRS detector 22 and to the ECG samples stored in buffer 21 to detect the onsets, peaks,

and offsets of the P and T waves in each ECG sample waveform. It is however important to understand that usage of the previously described QRS detector 22 is not essential to the operation of P and T detector 25. The prior art has evolved a variety of QRS detectors, many of which can detect onsets, peaks, and offsets of QRS waves in ECG sample waveforms. Any such QRS detector could readily be adapted and substituted for QRS detector 22 to serve as an input source of onsets, peaks, and offsets of QRS waves for P and T detector 25.

The operation of P and T detector 25 is conveniently characterized in terms of the following definitions:

MinPWidth	absolute minimum time between P wave onset and offset
MinPHeight	absolute minimum height from onset or offset to peak of P wave
MinTWidth	absolute minimum time between T wave onset and offset
MinTHeight	absolute minimum height from onset or offset to peak of T wave

With reference to Figure 7, step 70 defines a time interval "MaxPR" (Figure 90) seconds prior to the onset of the selected input QRS wave; and, a time interval "MaxST" seconds after the offset of the selected input QRS wave. Step 71 narrows the MaxPR interval, as shown in Figure 9P, so that it does not overlap any previously detected T or QRS wave, and narrows the MaxST interval so that it does not overlap the following QRS wave. Step 72 filters the input ECG samples obtained from buffer 21 to remove noise. As hereinafter described with reference to Figure 8, step 73 detects, in the narrowed MaxPR interval, the best candidate P wave which satisfies the MinPWidth and MinPHeight thresholds; and, step 74 detects, in the narrowed MaxST interval, the best candidate T wave which satisfies the MinTWidth and MinTHeight thresholds. Step 75 then outputs the P wave detected by step 73, if any; the T wave detected by step 74, if any; and the QRS wave previously detected by QRS detector 22.

Figure 8 provides greater detail of the operations performed during steps 73 and 74. The same operations are performed during each of steps 73 and 74, the only difference being that step 73 is performed with respect to the narrowed MaxPR interval to detect the best candidate P wave, and step 74 is performed with respect to the narrowed MaxST interval to detect the best candidate T wave. Accordingly, in the following description, reference is made to the "candidate wave", which those skilled in the art will understand to mean a candidate P wave if the Figure 8 operations are performed during step 73, and to mean a candidate T wave if the Figure 8 operations are performed during step 74.

The Figure 8 operations are conveniently characterized in terms of the following definitions:

MinWidth	minimum time between onset and offset of candidate wave
MinHeight	minimum height from onset or offset to peak of candidate wave
BestPeak	location of best candidate wave's peak
BestOn	location of best candidate wave's onset
BestOff	location of best candidate wave's offset
BestGamma	measure of best candidate wave's validity

Initialization step 80 sets the values of BestOn, BestOff, BestPeak, and BestGamma to nil, and sets the values of MinWidth and MinHeight to equal parameters passed into P and T detector 25. Step 81 initiates a loop which iteratively evaluates the "On" and "Off" values (Figure 9Q) for every pair of sample points within the input interval of the candidate wave (i.e. the narrowed MaxPR interval in the case of step 73, or the narrowed MaxST interval in the case of step 74) and selects the BestOn, BestOff, and BestPeak values for the candidate wave.

More particularly, a candidate onset value "On", and a candidate offset value "Off" are selected during step 81. Test step 82 then determines whether the time "T" (Figure 9Q) between the On and Off values is greater than MinWidth. If test step 82 determines that T is not greater than MinWidth then the loop is repeated commencing with step 81.

Otherwise, if test step 82 determines that T is greater than MinWidth, then step 83 is performed to determine the area "A" (Figure 9R) of the closed polygon bounded by all of the sample intervals between and including the On and Off values, the polygon having a base line "B" (Figure 9R) extending linearly between the On and Off values.

Step 84 then selects as the "Peak" sample (Figure 9S) the ECG sample which has the maximum height "h" above base line B. In this context, "height" refers to the distance in ECG samples from Peak to base line B. A test step 85 is then performed to determine whether h is greater than MinHeight. If test step 85 determines that h is not greater than MinHeight then the loop is repeated commencing with step 81.

Otherwise, if test step 85 determines that h is greater than MinHeight, step 86 is performed to determine the Euclidean distance "d" (Figure 9S) between the candidate On and Off values in terms of both ECG samples and time. Step 87 is then performed to determine a candidate value "Gamma" = A*h/d. Test step 88 is then performed to determine whether Gamma is greater than BestGamma. If test step 88 determines that Gamma is not greater than BestGamma then the loop is repeated commencing with step 81. Otherwise, if test step 88 determines that Gamma is greater than BestGamma, then the values of BestOn, BestOff, BestPeak, and BestGamma are replaced with the values of On, Off, Peak, and Gamma and the loop is then repeated commencing with step 81.

Summary

It will thus be understood that the apparatus depicted in Figure 5 receives input ECG samples, detects QRS waves in such samples, and then detects the P and T waves adjacent each QRS wave. The ECG samples are read from a sequential storage device and buffered in a computer memory. Approximations to the first and second derivatives of the ECG samples are also computed and buffered. The ECG

samples and the first and second derivative approximations are input to a QRS detector, which outputs the onsets, offsets and peaks of detected QRS waves.

The QRS detector maintains records of the last detected QRS (which is a provisional candidate for output as a valid QRS wave, until its final acceptance), and a QRS model derived from the last detected QRS. Final acceptance of the last QRS wave as a valid QRS wave depends upon the outcome of tests which involve the next candidate QRS wave. The QRS detector iterates over every ECG sample in the candidate wave, comparing each sample to the QRS model to determine whether the selected sample is the peak of a QRS wave. If no QRS is detected after a maximum expected QRS interval, the model parameters are relaxed and the ECG samples subsequent to the last valid QRS are re-examined. If the model is already fully relaxed, no new QRS is detected and the last detected QRS is accepted as valid and output.

Once an ECG sample is determined to be a candidate QRS peak, the candidate QRS wave's onset and offset are determined by setting thresholds and examining the first and second derivatives near the peak. The candidate peak, onset, and offset must satisfy the QRS model thresholds. If the candidate satisfies the model and is sufficiently far from the previous QRS, the previous QRS is output as a detected QRS wave. If the candidate satisfies the model but is too close to the previous QRS, the QRS having the lesser second derivative value at its peak is rejected. If the current candidate passes all tests, the last QRS is accepted as valid and output, and the current QRS candidate is recorded as the last QRS.

Once a QRS has been detected (either by QRS detector 25 or by a suitable substitute QRS detector), a P and T wave detector looks for a P wave preceding the QRS wave and for a T wave following it. These waves are found by finding waves in the ECG samples which satisfy minimum height and width requirements and lie near the QRS. The

ECG samples in these ranges are first filtered to remove noise. The onset and offset of the P and T waves are chosen according to their height relative to their onset and offset, the distance between their onset and offset, and the area of a closed polygon bounded by the ECG samples between their onset and offset. The P and T wave detector outputs include the onset, offset, and peaks of the P and T waves.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

WHAT IS CLAIMED IS:

1. A method of detecting P and T waves in an electrocardiogram signal containing said P and T waves and containing previously detected QRS waves, said method characterized by the steps of:

   a. selecting (41) a next one (QRSPeak) of said previously detected QRS waves;

   b. defining (70) a first time interval (MaxPR) within said electrocardiogram signal, said first time interval preceding said selected QRS wave and containing a plurality of samples of said electrocardiogram signal;

   c. defining (70) a second time interval (MaxST) within said electrocardiogram signal, said second time interval following said selected QRS wave and containing a plurality of samples of said electrocardiogram signal;

   d. narrowing (71) said first time interval to exclude QRS and previously detected T waves preceding said selected QRS wave;

   e. narrowing (71) said second time interval to exclude QRS waves following said selected QRS wave;

   f. for each pair of said samples in said first time interval:

      i. proceeding (82) to step 1(f)(iv) if said pair of samples are separated by a time duration which does not exceed a predefined time duration (MinPWidth);

      ii. deriving (83) the area, width, and height of a closed polygon having vertices defined by all samples within said first time interval between and including said pair of samples;

      iii. deriving (86, 87) a rating for said polygon as a function of said area, width and height;

iv. selecting (81) another pair of said samples and proceeding to step 1(f)(i);

g. selecting (73) as said P wave that one of said step 1(f)(iii) polygons for which said rating is maximal;

h. for each pair of said samples in said second time interval:

i. proceeding (82) to step 1(h)(iv) if said pair of samples are separated by a time duration which does not exceed a predefined time duration (MinTWidth);

ii. deriving (83) the area, width, and height of a closed polygon having vertices defined by all samples within said second time interval between and including said pair of samples;

iii. deriving (86, 87) a rating for said polygon as a function of said area, width and height;

iv. selecting (81) another pair of said samples and proceeding to step 1(h)(i); and,

i. selecting (74) as said T wave that one of said step 1(h)(iii) polygons for which said rating is maximal.

2. A method as defined in claim 1, further comprising, before said step 1(f), the further step of filtering (72) those portions of said electrocardiogram signal containing said first and second time intervals to remove noise.

3. A method as defined in claim 1, wherein said previously detected QRS waves are respectively characterized by onset (QRSOn), offset (QRSOff) and peak (QRSPeak) values, said method further comprising detecting said onset, offset and peak values by:

a. deriving first and second derivative approximations (D1, D2) of said electrocardiogram signal;

b. deriving from said previously detected QRS waves a plurality of threshold values (D2Thresh, MinD2-

Height, MinHeight, MinWidth) which collectively characterize acceptable bounds for said onset, offset and peak values;

c. for each of said previously detected QRS waves, selecting candidate values for said onset, offset and peak values;

d. comparing said candidate values to said threshold values to derive a measure of difference therebetween;

e. accepting said candidate values as said onset, offset and peak values respectively if said difference does not exceed a predefined minimum; and,

f. if said difference exceeds said predefined minimum, increasing said respective threshold values and proceeding to said step 3(c).

4. A method as defined in claim 1, wherein said steps 1(f)(ii) and 1(h)(ii) each further comprise:

a. deriving said closed polygon area as that area bounded by all of said samples between and including said pair of samples, said polygon having a base line extending linearly a distance "d" between said pair of samples;

b. deriving a maximum vertical displacement "h" between said base line and any portion of said polygon above said base line; and,

c. comparing said maximum vertical displacement to a predefined minimum vertical displacement; and,

d. if said maximum vertical displacement exceeds said predefined minimum vertical displacement then defining said rating = A*h/d for said pair of samples.

5. A method as defined in claim 1, wherein:

a. said narrowing step 1(d) further comprises:

i. if said first time interval overlaps a time interval occupied by a previously detected T wave portion of said electrocardiogram

signal preceding said first time interval, reducing (71) said first time interval to exclude said previously detected T wave portion;

ii. if said first time interval overlaps a time interval occupied by a previously detected QRS wave portion of said electrocardiogram signal preceding said first time interval, reducing (71) said first time interval to exclude said previously detected QRS wave portion; and,

b. said narrowing step 1(e) further comprises:

i. if said second time interval overlaps a time interval occupied by a previously detected QRS wave portion of said electrocardiogram signal following said second time interval, reducing (71) said second time interval to exclude said previously detected QRS wave portion.

6. A method as defined in claim 1, wherein said previously detected QRS waves are detected by, for each pair of samples within said respective first and second time intervals:

a. deriving first and second derivative approximations (D1, D2) of said electrocardiogram signal;

b. comparing (47, 48) said second derivative approximations and selecting as a first peak that one of said samples for which said second derivative approximation is greatest;

c. proceeding to step 6(q) if said first peak second derivative approximation does not exceed a predefined minimum second derivative approximation value;

d. comparing (47, 48) said second derivative approximations for said samples immediately preceding said first peak and selecting as a second peak

that one of said preceding samples for which said second derivative approximation is greatest;

e. comparing (47, 48) said second derivative approximations for said samples immediately following said first peak and selecting as a third peak that one of said following samples for which said second derivative approximation is greatest;

f. proceeding (50) to step 6(q) if said second and third peaks are separated by a time duration which exceeds a predefined maximum onset-offset time duration;

g. proceeding (51) to step 6(q) if the difference between said first and second peak second derivative approximations does not exceed a predefined minimum peak separation value or if the difference between said first and third peak second derivative approximations does not exceed said predefined minimum peak separation value;

h. defining (52) a first threshold D1L as a function of said first derivative approximations for said samples between said first and second peaks;

i. defining (52) a second threshold D1R as a function of said first derivative approximations for said samples between said first and third peaks;

j. defining (52) a third threshold D2LR as a function of said second derivative approximations for said samples between said first and third peaks;

k. selecting (53) as a QRSOn value that one of said samples for which said first and second derivative approximations respectively do not exceed said D1L and D2LR thresholds;

l. selecting (53) as a QRSOff value that one of said samples for which said first and second derivative approximations respectively do not exceed said D1R and D2LR thresholds;

m. proceeding (54) to step 6(q) if said selected QRSOn and QRSOff values are separated by a time

duration which does not exceed a predefined QRS time duration;

n. if said selected QRSOn and QRSOff values are separated by a time duration which exceeds said predefined QRS time duration then selecting (55) said second peak as said QRSOn value and selecting said third peak as said QRSOff value;

o. proceeding (56) to step 6(q) if the average values of:

i. said samples between said first peak and said QRSOn value;

ii. said samples between said first peak and said QRSOff value;

do not exceed a predefined average value;

p. if said first peak is not separated from said first peak of an immediately preceding, previously detected QRS wave then rejecting (59) that one of said samples for which said second derivative approximation is lowest; and,

q. selecting (41) a next pair of said samples and repeating steps 6(a) through 6(p) until none of said samples remain.

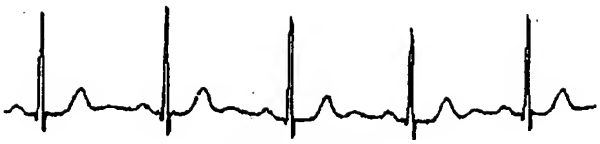


FIGURE 1

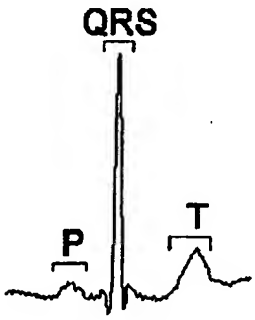


FIGURE 2

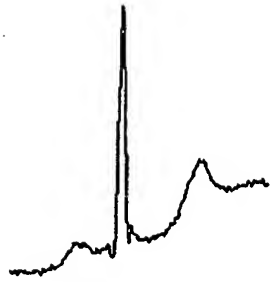


FIGURE 3

FIGURE 4

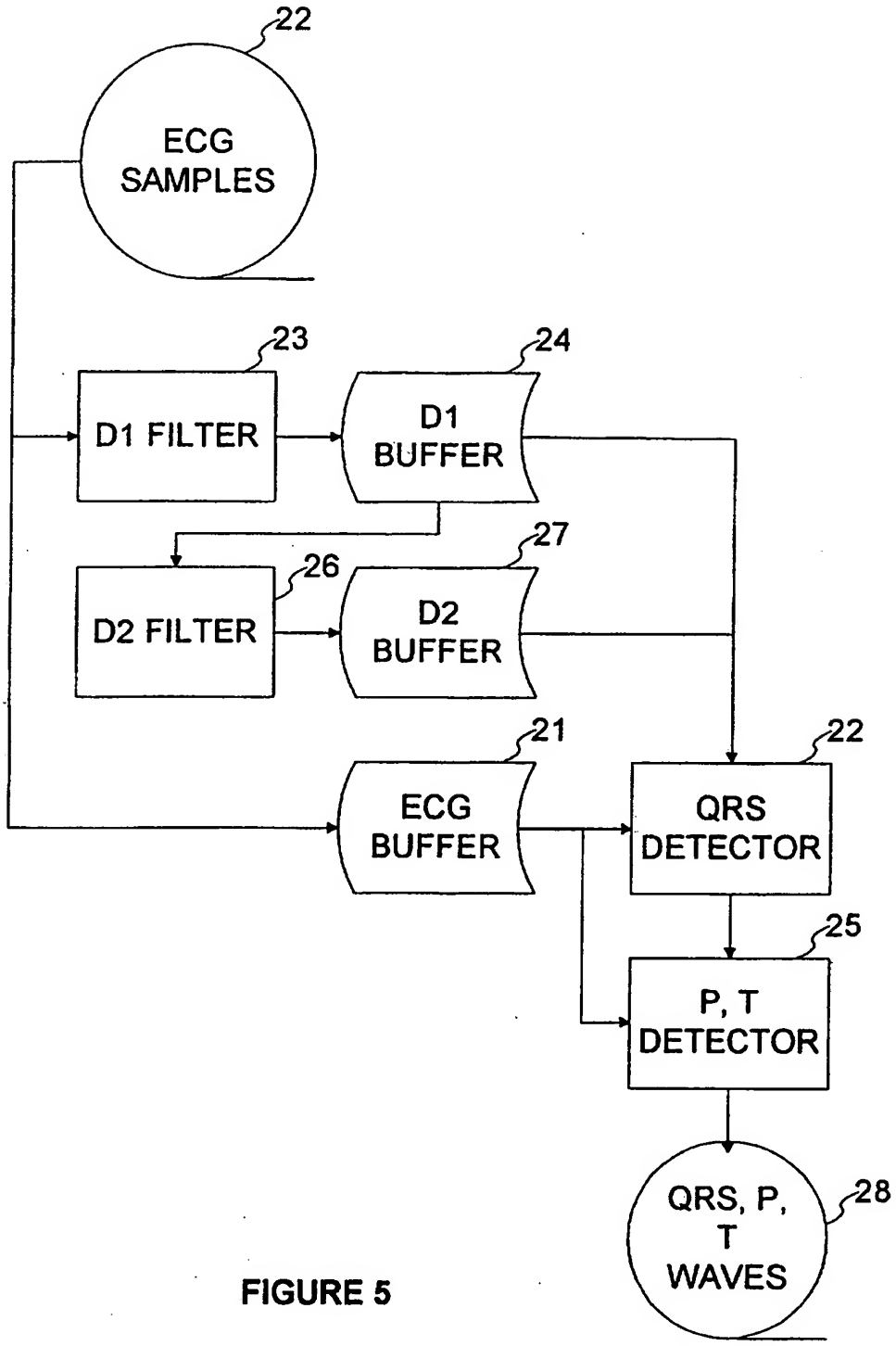

22
ECG SAMPLES
23
D1 FILTER
24
D1 BUFFER
27
26
D2 FILTER
D2 BUFFER
21
22
ECG BUFFER
QRS DETECTOR
25
P, T DETECTOR
QRS, P, T WAVES
28

FIGURE 5

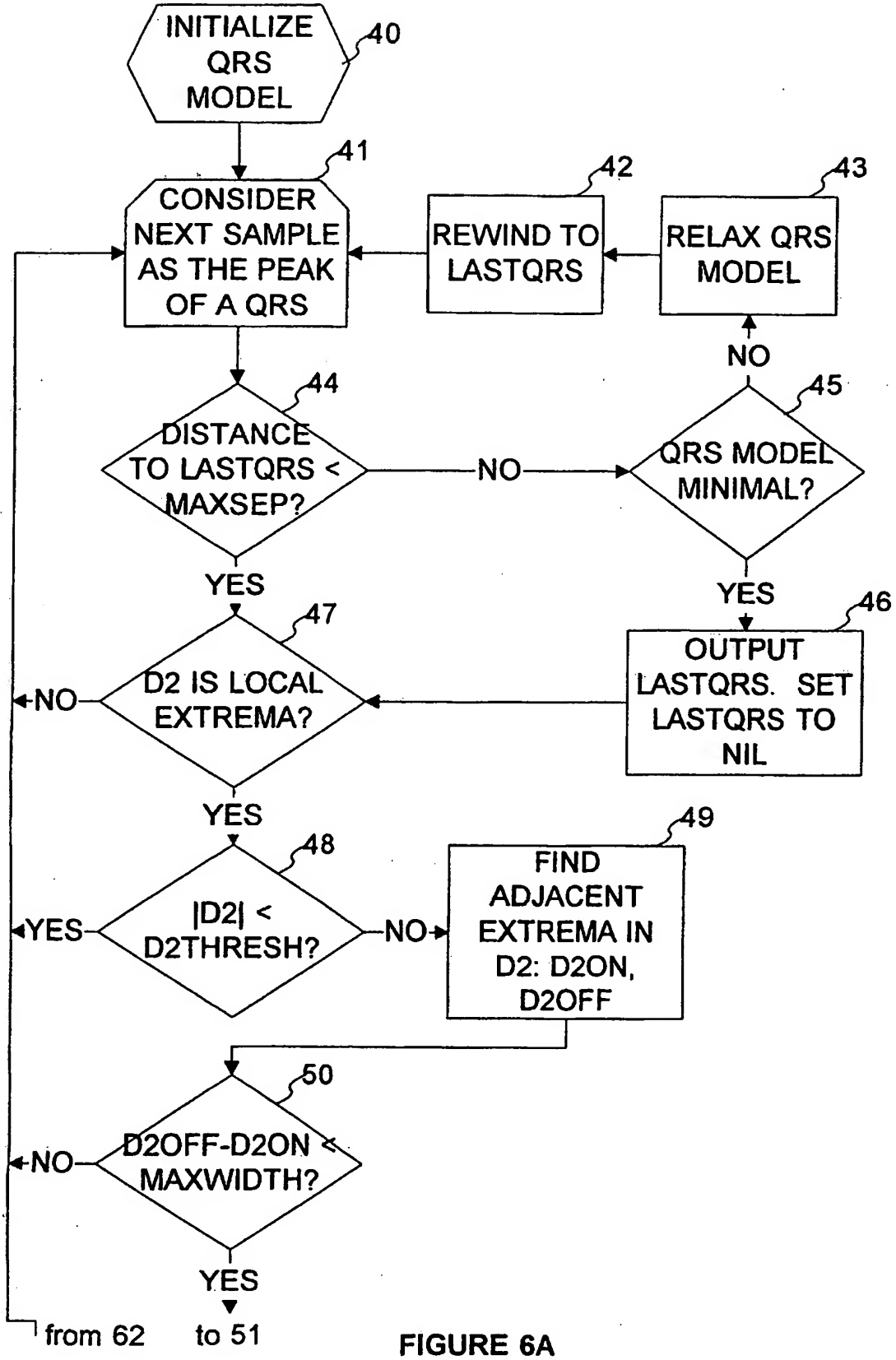

INITIALIZE QRS MODEL
40
CONSIDER NEXT SAMPLE AS THE PEAK OF A QRS
41
REWIND TO LASTQRS
42
RELAX QRS MODEL
43
NO
DISTANCE TO LASTQRS < MAXSEP?
44
NO
QRS MODEL MINIMAL?
45
YES
YES
OUTPUT LASTQRS. SET LASTQRS TO NIL
46
D2 IS LOCAL EXTREMA?
47
NO
YES
|D2| < D2THRESH?
48
YES
NO
FIND ADJACENT EXTREMA IN D2: D2ON, D2OFF
49
D2OFF-D2ON < MAXWIDTH?
50
NO
YES
from 62
to 51

FIGURE 6A

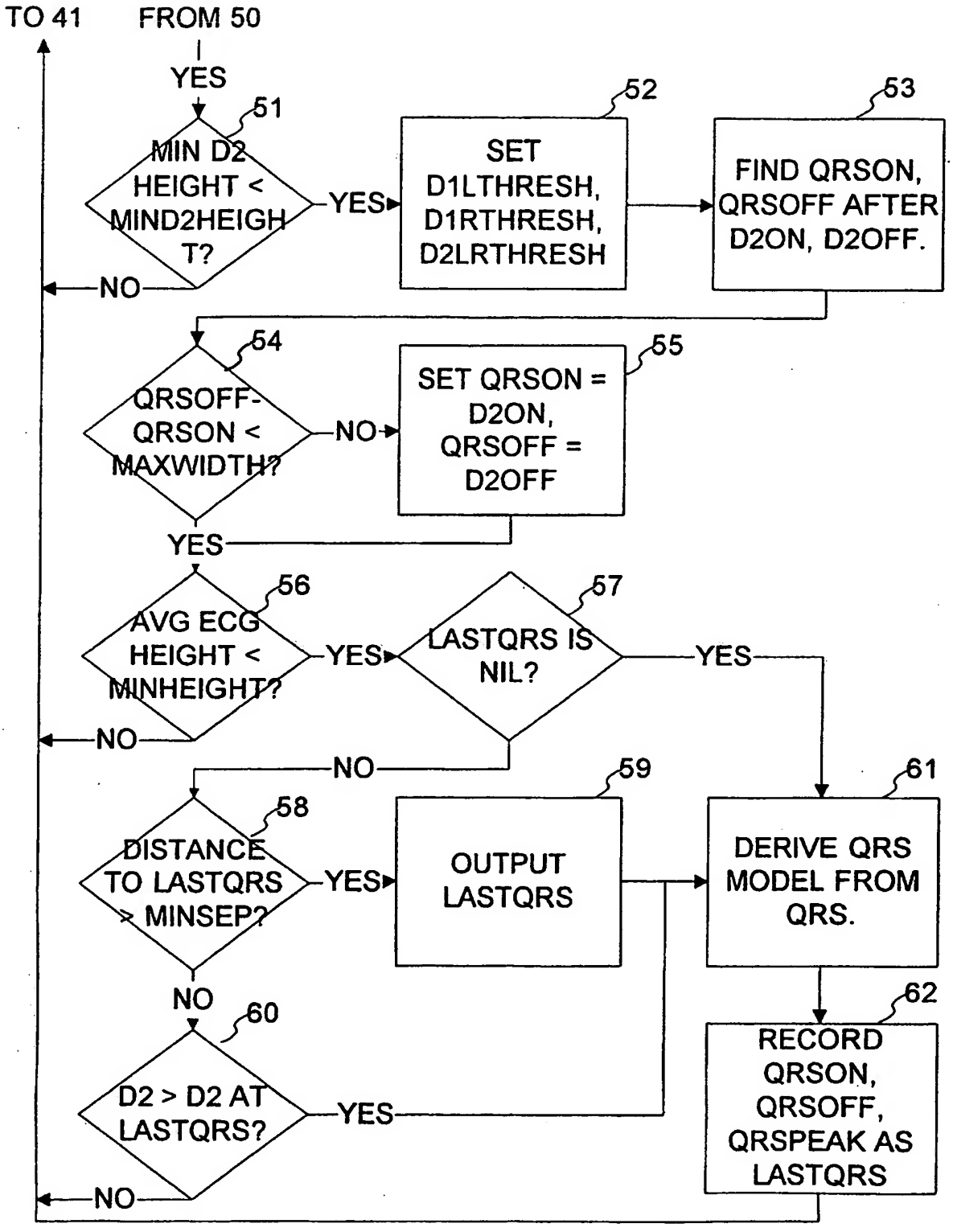

TO 41
FROM 50
YES
51
MIN D2 HEIGHT < MIND2HEIGHT?
YES
NO
52
SET D1LTHRESH, D1RTHRESH, D2LRTHRESH
53
FIND QRSON, QRSOFF AFTER D2ON, D2OFF.
54
QRSOFF-QRSON < MAXWIDTH?
NO
55
SET QRSON = D2ON, QRSOFF = D2OFF
YES
56
AVG ECG HEIGHT < MINHEIGHT?
YES
57
LASTQRS IS NIL?
YES
NO
NO
58
DISTANCE TO LASTQRS > MINSEP?
YES
59
OUTPUT LASTQRS
61
DERIVE QRS MODEL FROM QRS.
NO
60
D2 > D2 AT LASTQRS?
YES
62
RECORD QRSON, QRSOFF, QRSPEAK AS LASTQRS
NO

FIGURE 6B

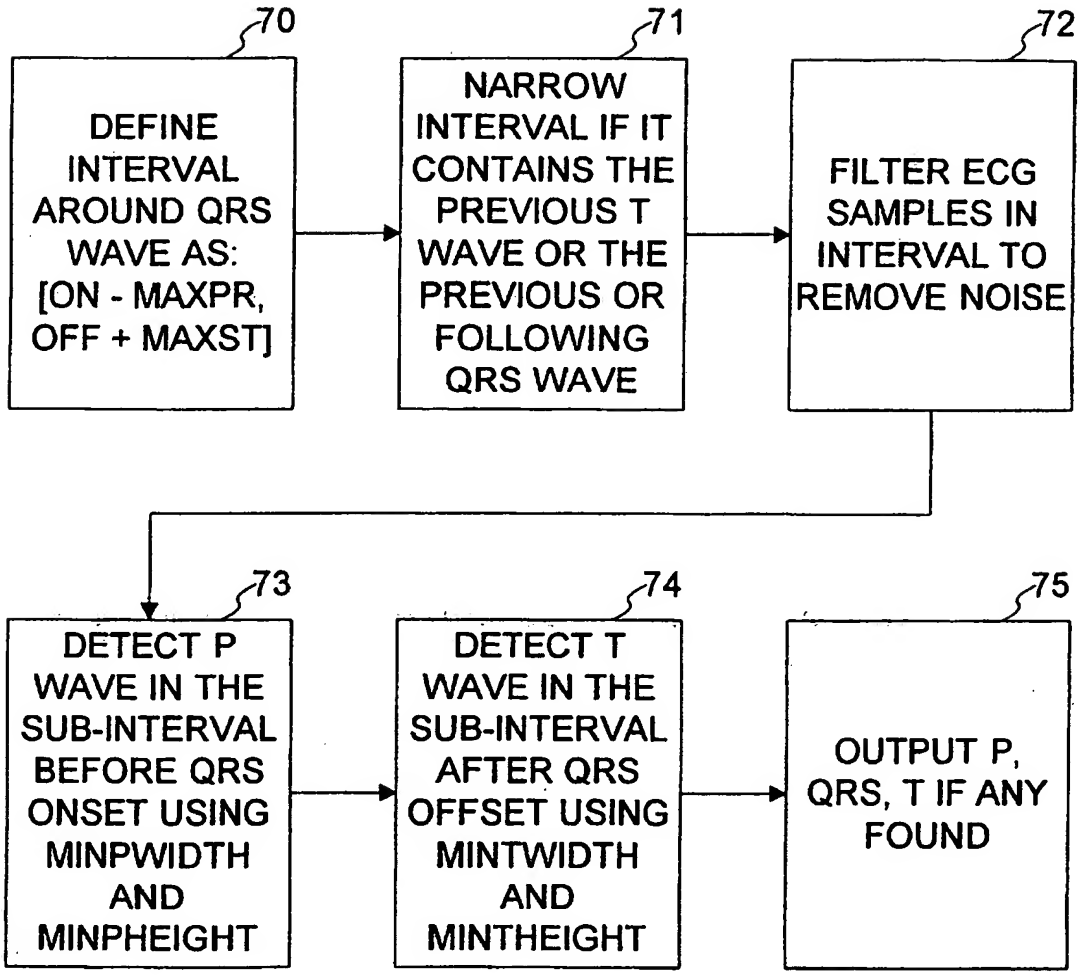

70
DEFINE INTERVAL AROUND QRS WAVE AS: [ON - MAXPR, OFF + MAXST]
71
NARROW INTERVAL IF IT CONTAINS THE PREVIOUS T WAVE OR THE PREVIOUS OR FOLLOWING QRS WAVE
72
FILTER ECG SAMPLES IN INTERVAL TO REMOVE NOISE
73
DETECT P WAVE IN THE SUB-INTERVAL BEFORE QRS ONSET USING MINPWIDTH AND MINPHEIGHT
74
DETECT T WAVE IN THE SUB-INTERVAL AFTER QRS OFFSET USING MINTWIDTH AND MINTHEIGHT
75
OUTPUT P, QRS, T IF ANY FOUND

FIGURE 7

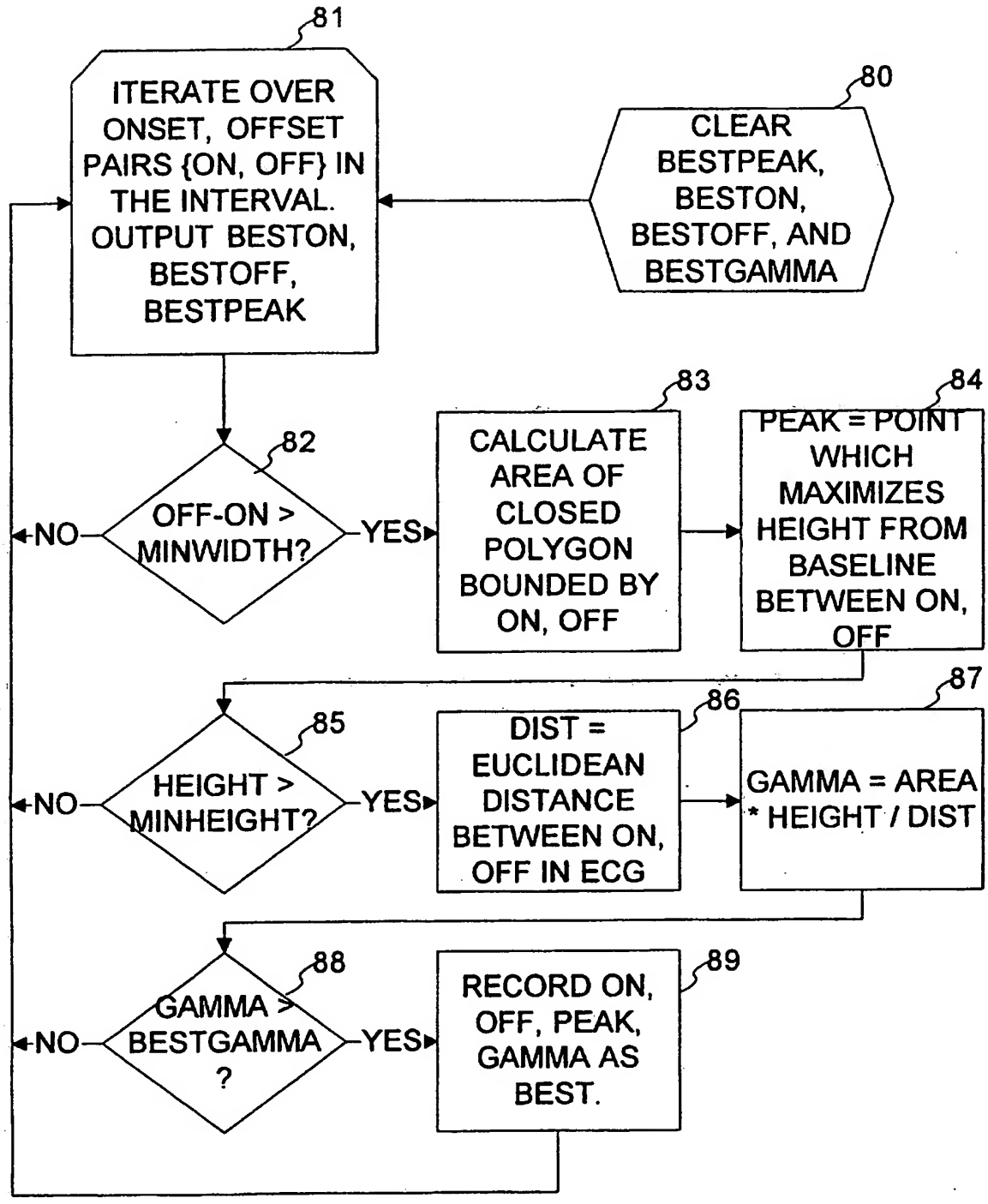

81
ITERATE OVER ONSET, OFFSET PAIRS {ON, OFF} IN THE INTERVAL. OUTPUT BESTON, BESTOFF, BESTPEAK
80
CLEAR BESTPEAK, BESTON, BESTOFF, AND BESTGAMMA
82
OFF-ON > MINWIDTH?
NO
YES
83
CALCULATE AREA OF CLOSED POLYGON BOUNDED BY ON, OFF
84
PEAK = POINT WHICH MAXIMIZES HEIGHT FROM BASELINE BETWEEN ON, OFF
85
HEIGHT > MINHEIGHT?
NO
YES
86
DIST = EUCLIDEAN DISTANCE BETWEEN ON, OFF IN ECG
87
GAMMA = AREA * HEIGHT / DIST
88
GAMMA > BESTGAMMA ?
NO
YES
89
RECORD ON, OFF, PEAK, GAMMA AS BEST.

FIGURE 8

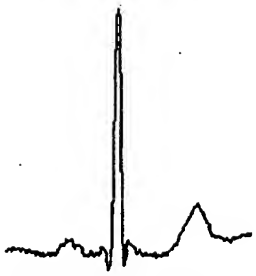


FIGURE 9A

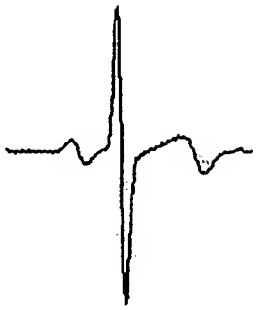


FIGURE 9B

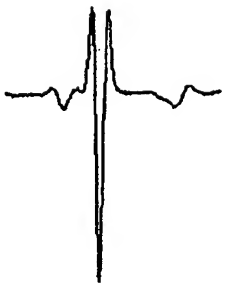


FIGURE 9C

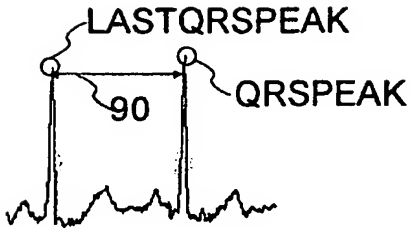


FIGURE 9D

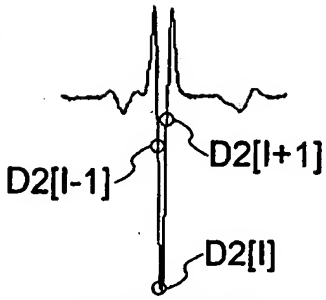


FIGURE 9E

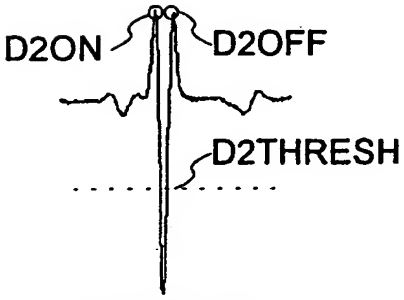


FIGURE 9F

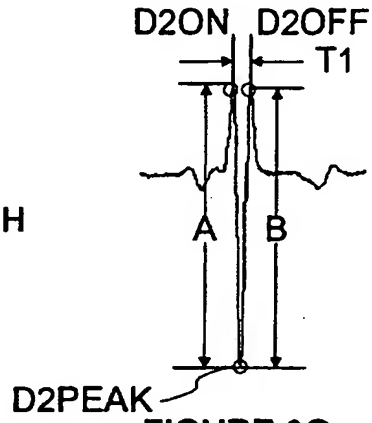


FIGURE 9G

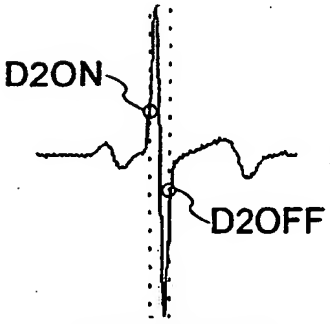


FIGURE 9H

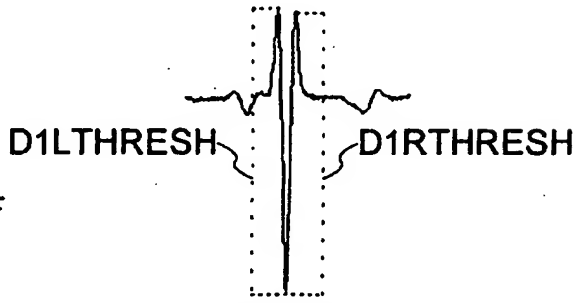


FIGURE 9I

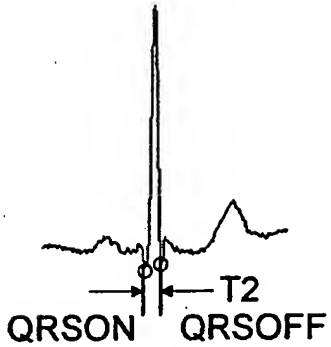


FIGURE 9J

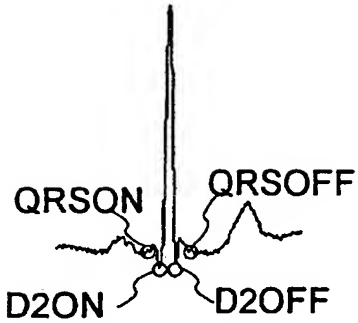


FIGURE 9K

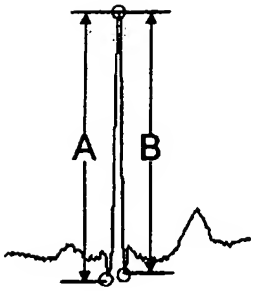


FIGURE 9L

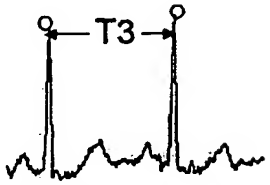


FIGURE 9M

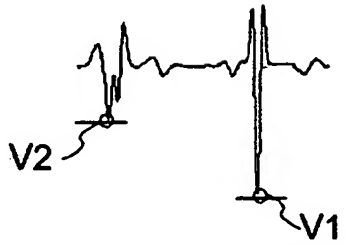


FIGURE 9N

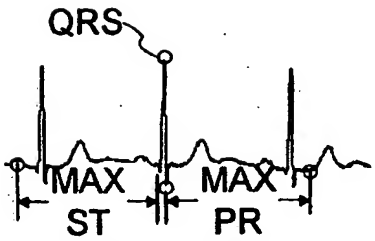


FIGURE 9O

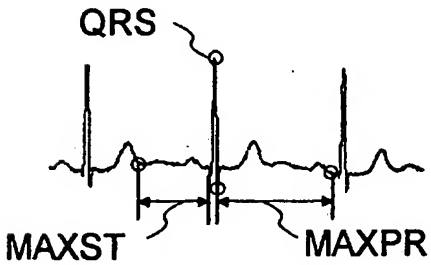


FIGURE 9P

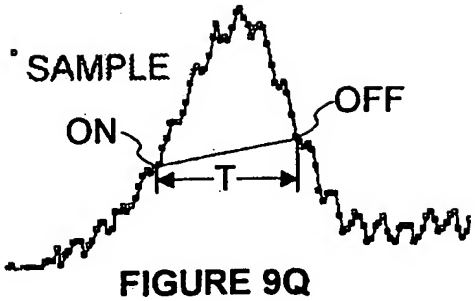


FIGURE 9Q

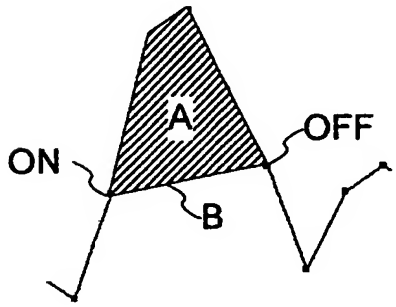


FIGURE 9R

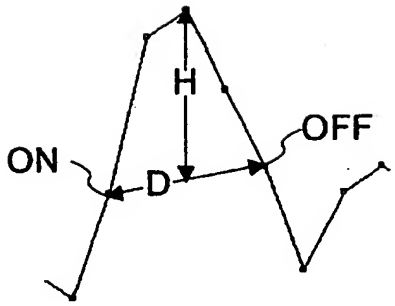


FIGURE 9S

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00615

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G06F19/00 A61B5/042

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06F A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ANONYMOUS: "Selective Filter for Electrocardiograph" IBM TECHNICAL DISCLOSURE BULLETIN, vol. 29, no. 4, September 1986, NEW YORK, US, pages 1797-1798, XP002046705 see the whole document ---	1
A	HEE-KYO JOENG ET AL: "A NEW ALGORITHM FOR P-WAVE DETECTION IN THE ECG SIGNAL" IMAGES OF THE TWENTY FIRST CENTURY, SEATTLE, NOV. 9 - 12, 1989, vol. 11 PART 1/06, 9 November 1989, YONGMIN KIM;SPELMAN F A, page 42/43 XP000129189 see the whole document ---	1

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 November 1997	27. 11. 97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Deane, E

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Interna .ial Application No
PCT/CA 97/00615

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3 832 994 A (BICHER H ET AL) 3 September 1974 see column 13, line 18 - column 15, line 22; figure 6 ---	1
A	FOKAPU O ET AL: "A NEW APPROACH FOR P WAVE DETECTION USING ANALYTIC SIGNAL" VISUALIZATION, IMAGING, SIGNAL PROCESSING, MODELING, NEURAL NETWORK, SAN DIEGO, OCT. 28 - 31, 1993, vol. 15 PART 1, 28 October 1993, SZETO A;RANGARAJ M RANGAYYAN, page 400/401 XP000436800 see the whole document ---	1
A	FREEMAN K ET AL: "P WAVE DETECTION OF AMBULATORY ECG" PROCEEDINGS OF THE ANNUAL INTERNATIONAL CONFERENCE OF THE ENGINEERI IN MEDICINE AND BIOLOGY SOCIETY, ORLANDO, OCT. 31 - NOV. 3, 1991, vol. 13, 31 October 1991, NAGEL J;SMITH W M, pages 647-648, XP000348272 see the whole document ---	1
A	LAGUNA P. ET AL.: "Automatic Detection of Wave Boundaries in Multilead ECG Signals: Validation with the CSE Database" COMPUTERS AND BIOMEDICAL RESEARCH, vol. 27, 1994, pages 45-30, XP002046491 cited in the application see page 49, line 23 - page 51, line 13 -----	1

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/CA 97/00615

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3832994 A	03-09-74	NONE	